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Arturo I. Quintanar
Universidad Nacional Autonoma de Mexico, arturo.quintanar@atmosfera.unam.mx

Rezaul Mahmood
University of Nebraska-Lincoln, rmahmood2@unl.edu

John H. Loughrin
USDA/ARS, Animal Waste Management Research Unit

Nanh Lovanh
USDA/ARS, Animal Waste Management Research Unit

Monica V. Motley
Western Kentucky University

A SYSTEM FOR ESTIMATING BOWEN RATIO AND EVAPORATION FROM WASTE LAGOONS

A. I. Quintanar, R. Mahmood, J. H. Loughrin, N. Lovanh, M. V. Motley

ABSTRACT. *A low-cost system was deployed above a swine waste lagoon to obtain estimates of Bowen ratios and characterize lagoon temperatures. The system consisted of humidity and temperature sensors and anemometers deployed above the lagoon, water temperature sensors, and a meteorological station located by the lagoon. To evaluate the system, data was analyzed from the 25th through 28th June 2007. Bowen ratios showed diurnal behavior near the lagoon surface characterized by negative values during day and positive ones at night. Latent (evaporation) and sensible heat fluxes were towards the atmosphere and the lagoon, respectively for most of the day. A diurnal cycle in atmospheric and lagoon temperatures was also observed. Furthermore, wind speeds above the lagoon were highest in the afternoon. These variations were linked to lagoon temperature stratifications which became more pronounced as wind speeds increased. Temperature stratification at the lagoon indicated increased heat exchange at the lagoon's interface with the atmosphere. During the night, the stratification disappeared and temperatures in the water column were almost identical down to about 60 cm. This behavior is similar to that observed in other shallow water bodies that are fetch-limited. Lagoon heating was driven by the diurnal cycle of solar radiation and net radiation. This suggests that Bowen ratios had an inverse relationship with lagoon heating and its thermal stratification. This also indicates that there was an increase in latent heat flux and evaporation during the daytime. These results are important for characterizing the thermal behavior of the lagoon leading to a better representation of processes responsible for emissions.*

Keywords. *Bowen Ratio, Evaporation, Energy flux, Thermal stratification.*

Anaerobic lagoons are effective and low-cost tools to treat animal waste. They are also responsible for emissions of pollutants including CO_2, NH_3, and indoles. Emission of these pollutants is controlled by interactions with the atmosphere as well as biochemical and physical processes occurring at the lagoon interface. Sulfides and volatile organic compounds (VOC) such as skatole, cresol, and indole are thought to be important constituents of offensive odors and a cause of discomfort and disease in the environment within and near confined animal feeding operations (CAFOs) (Cole et al., 2000). Thus, any study on emissions from CAFOs needs to address the issue of anaerobic lagoons as a source of atmospheric pollutants (Loughrin et al., 2006). Despite their relatively small size, compared to lakes or estuaries for instance, lagoons exhibit considerable complexity when interacting with the atmosphere. This complexity is reflected in the interactions that take place between the atmospheric boundary layer and the lagoon. Wind stress can drive lagoon surface circulation and stir the upper layers leading to mixing which affect VOC emissions. This effect is a function of wind magnitude, the stability within the atmospheric boundary layer, and the roughness discontinuity that exists between the lagoon and its surroundings which perturbs (or advects) the air as it crosses downwind over the leading edge (Oke, 1987; Stull, 1988; Stannard, 1997; Wilson et al., 2001).

The exchange of mass and energy at the interface of the lagoon is one aspect of this interaction that is of particular interest to researchers since water vapor fluxes can be used to estimate gas emissions (Wilson et al., 2001; Griffith et al., 2002; DeSutter and Ham, 2005). Additionally, waste lagoons operate within certain technical limits that require knowledge of evaporation rates, seepage losses, and water mass balance estimates (Ham, 1999). The available energy at the lagoon surface (i.e., the net radiation minus the heating of the lagoon water column) is used to evaporate water from a thin film at the lagoon surface. The ratio of sensible to latent heat flux is a measure of how this available energy is partitioned at the atmosphere-lagoon interface and is known as the Bowen ratio.

Two different methods exist to estimate Bowen ratio from measurements of sensible and latent heat fluxes. One of these is based on the eddy covariance (EC) concept where the fluxes are represented as the correlation between fast time-varying fluctuations of vertical velocity, temperature, and moisture fields. A second method is to represent energy fluxes as proportional to the vertical gradients of temperature and moisture to infer heat fluxes from imposing energy balance at the surface (Bowen ratio energy balance method

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The authors are **Arturo I. Quintanar,** Post-Doctoral Scholar, Department of Geography and Geology, Western Kentucky University, Bowling Green, Kentucky; **Rezaul Mahmood,** Associate Professor, Department of Geography and Geology, Western Kentucky University, Bowling Green, Kentucky; **John H. Loughrin,** Research Chemist, USDA/ARS, Animal Waste Management Research Unit, Bowling Green, Kentucky; **Nanh Lovanh, ASABE Member Engineer,** Environmental Engineer, USDA/ARS, Animal Waste Management Research Unit, Bowling Green, Kentucky; and **Monica V. Motley,** Student, Department of Geography and Geology, Western Kentucky University, Bowling Green, Kentucky. **Corresponding author:** Arturo I. Quintanar, Department of Geography and Geology, Western Kentucky University, 1 Big Red Way, Bowling Green, KY 42101; phone: 270-745-2634; fax: 270-745-6410; e-mail: Arturo.quintanar@wku.edu.

or BREB). Both methods have advantages and disadvantages which have been discussed at length in the literature (e. g., Brotzge and Crawford, 2002; Gavin and Agnew, 2003). In our case, a key consideration was cost. We wished to construct a relatively low cost and robust system that could be deployed for an extended period of time above the surface of a waste treatment lagoon. Based on this criterion, we chose the latter method not only due to its relatively low cost of implementation as compared to an eddy covariance system, but also due to its presumed robustness when deployed in the relatively dirty environment above a waste treatment lagoon.

Bowen ratio has been used as an index in climatological and meteorological studies to evaluate energy partitions under a variety of surface characteristics (Perez et al., 2008). Estimations have been used to signify characteristics of energy fluxes and evaporation over forest, arid areas, lakes, ponds, oceans, and crops (Penman, 1948; Priestley and Taylor, 1972; McCaughey and Brintell, 1984; Spence et al., 2003; Irmak and Irmak, 2008). However, because of potential uncertainties due to instrument errors, fetch effects and thermal gradient effects from adjacent drier areas, the reliability of Bowen ratio and evaporation rates estimates using BREB have been the focus of several studies (Ohmura, 1982; Perez et al., 1999; Gavilan and Berengena, 2007; Guo et al., 2007). As a result, one objective of this study was to investigate how evaporation estimates using a BREB method and their reliability compared to the classical Penman (1948) method. BREB estimates for two heights were used to verify that the sampling of data was done correctly (thus BREB calculation) and to characterize the lagoon and its interactions with the immediate overlying atmosphere.

Another aspect of the atmosphere-lagoon interaction is lagoon circulation and thermodynamic response. There is paucity of data regarding thermal stratification of waste lagoons as a response to atmospheric and radiative forcing. This is an important control on emissions since it can limit the vertical transfer of oxygen and other dissolved gases through the water column (Hocking and Patterson, 1994). This lack of oxygenation favors the production of ammonia from the bottom sludge (Condie and Webster, 2001). As a result, another objective of this study was to investigate the relationship between thermal stratification in the lagoon and Bowen ratios to gain insight into processes affecting evaporation. This study is part of a larger project investigating the atmospheric conditions that affect emissions from animal waste lagoons (e. g., Quintanar et al, 2008; Quintanar et al, 2009).

Materials and Methods

Experimental Site

The research area was located at Logan County (36° 42' N, 86° 42' W) in Kentucky at a farrowing farm of approximately 2,000 sows. An anaerobic lagoon of 65 × 65 m and 3 m in depth was used to treat wastewater from four houses. The surrounding land use can be characterized as mostly crop land. Data collection occurred from 25 to 28 June 2007.

Instrumentation

A HOBO weather station (H21-001, Onset Computer Inc., Bourne, Mass.) was located about 20 m from the southwest corner of the lagoon. It was equipped with anemometer at 3 m above the ground, temperature and relative humidity sensors, silicon pyranometer (spectral range of 300 to 1,100 nm), and a barometer, all placed 2 m above the ground. Additional sensors were deployed at the lagoon. These included two sets of temperature and relative humidity sensors (HOBO Pro V2 U22/001) at heights of 0.5 and 1.5 m above the lagoon surface by means of a raft constructed from polyvinylchloride (PVC) pipe. To estimate heat fluxes from the lagoon, additional HOBO Water Temperature Pro V2 temperature sensors were attached to a vertical cable supported by a buoy with sensors deployed at the surface, 0.3, 0.6, and 0.9 m below the surface of the lagoon. The temperature sensors for both the HOBO weather station and those deployed at the lagoon had an accuracy of ±0.2°C over 0° to 50°C and a resolution of 0.02°C at 25°C. Similarly, the relative humidity sensors had an accuracy of ±2.5% from 10% to 90% and a resolution of 0.03%.The response time of the humidity sensors at 90% relative humidity is about 40 min in air moving at 1 m s^{-1} and had a drift of less than 1% per year.

Another raft constructed from PVC pipe supported anemometers (APRS 6500, APRS World, Winona, Minn.) also placed 0.5 and 1.5 m above the lagoon surface. The accuracy of the instruments was ±0.4 m s^{-1} with a resolution of about 0.1 m s^{-1}. The lowest wind speed measurable was 0.5 m s^{-1}. The anemometers were connected by a water-proof cable to a solar-powered data collection station located on the lagoon bank. Care was taken to maintain both rafts at fixed points near the center of the lagoon with anchors and holding cables attached to the lagoon bank. In all cases, data was recorded every 5 min and hourly time series was produced from these data.

Bowen Ratio

Using flux-gradient techniques to approximate the turbulent sensible and latent heat fluxes, Bowen ratio can be shown to be proportional to the ratio of temperature and water vapor vertical mean gradients (Stull, 1988). In practice, when not using eddy correlation techniques with the aid of sonic anemometers, we compute Bowen ratio as:

$$B = \frac{c_p}{L} \frac{\overline{\Theta}(z_1) - \overline{\Theta}(z_2)}{\overline{r}(z_1) - \overline{r}(z_2)} \qquad (1)$$

Figure 1. Humidity/temperature sensors and anemometers deployed above the lagoon surface.

where B is the Bowen ratio, C_p is the specific heat of air at constant pressure, and L is latent the heat of vaporization and the overbar refers to hourly averages. The ratio of C_p / L is considered here as 0.4 K^{-1} at 25°C (Oke, 1987; Stull, 1988), Θ is potential temperature (K), and r is mixing ratio calculated from two different heights on the masts of rafts at 0.5 m (z_2) and 1.5 m (z_2) above the lagoon surface. Implicit in the derivation of the Bowen ratio is the assumption that turbulent eddy diffusivities are the same for heat and mass transfer across the lagoon's interface. Mixing ratio is computed from measurements of relative humidity at the two heights as:

$$r(z_i) = \varepsilon \frac{RH(z_i) e_s(T(z_i))}{p(z_i) - RH(z_i) e_s(T(z_i))} \tag{2}$$

where ε = 0.622 is the ratio of gas constants for dry air to that of water vapor, $RH(z_i)$ is relative humidity at height z_i.The pressure $p(z_i)$ is computed hydrostatically from the pressure measurements at the weather station and the known elevation of the sensors at the raft relative to the elevation of weather station. The saturation vapor pressure $e_s(T)$ was computed from Murray (1967) and potential temperature was calculated directly using the same pressure estimates as mentioned above and the corresponding temperatures. The estimations of Bowen ratio were done from hourly estimates of all the above variables. In addition to computing Bowen ratio from 1.5- and 0.5-m heights (BR1), we also computed Bowen ratio from the 0.5 m and the surface of the lagoon (SFC) (BR2). In the latter case, we assumed that the air was saturated (RH=100%) at the surface. Bowen ratio was also estimated from 1.5 m and SFC. However, results were not included in this article because estimates were very similar to BR2. Since the differences in Bowen ratio estimates were greater between BR1 and BR2, we were more interested in the impacts of these differences in energy flux estimates and the evaporation.

EVAPORATION

Evaporation is difficult to estimate because of the number of measured variables necessary to close the budget. A series of assumptions and corrections was made to account for local differences to arrive at a representative estimate. Several models exist for the estimation of evaporation from open water bodies. The Penman (1948) model was our choice since measurements of radiation, temperature at the surface of the water, relative humidity, and wind speed were available. The expression for evaporation derived by Penman (Penman, 1948) is a combination of an energy term which is a function of the available energy and an aerodynamic term which is a measure of the capacity of the atmosphere to transport water vapor (Oke, 1987; Brutsaert, 2005). The evaporation E (kg m^{-2} s^{-1}) estimation by the Penman method (Penman, 1948) can be expressed as (Brutsaert, 2005):

$$E = \frac{\Delta}{\Delta + \gamma}\left(\frac{Rn - G}{L}\right) + \frac{\gamma}{\Delta + \gamma} C_e U_i \left(\frac{0.622}{R_d T_i}\right)(e_s(T_i) - e_a(T_i)) \tag{3}$$

Here, T_i is the temperature of the air, and U_i is the wind speed both measured at height z_i above the surface of the lagoon and R_d is the gas constant for dry air. Equation 3 contains the available energy term $R_n - G$, where R_n is net radiation (Wm^{-2}) approximated as: $R_n = 0.87\, R_s - 49$ and R_s is global solar radiation (Ham, 1999). Δ is the slope of the saturation vapor pressure curve and γ is the psychrometric constant. We have assumed $\gamma = (p\,(z_i)Cp)/(0.622\, L)$. In equation 3, $e_s\,(T_i)$ is the saturation vapor pressure (Pa) calculated from Murray (1967) and $e_a\,(T_i)$ the corresponding actual vapor pressure (Pa) as a function of temperature measured at z_i. Thus, the $(e_s\,(T_i) - e_a\,(T_i))$ is the vapor pressure deficit at that level. C_e is a water vapor transfer coefficient for neutral conditions and can be expressed as:

$$C_e = \frac{k^2}{\ln^2(z_i / z_0)} \tag{4}$$

where k is the von Karman's constant (0.4) and z_0 is the roughness length (0.0001 m) for the lagoon (Oke, 1987).

Finally, G (Wm^{-2}) is heat storage into the lagoon and L is the latent heat of vaporization of water (2442 J kg^{-1}).

G is calculated from time change of subsurface temperature measurements Tw_i, as:

$$G = \rho C_p \sum_1^n \frac{\Delta Tw_i}{\Delta t} \Delta z_i \tag{5}$$

where ρ is density of water and Δz_i is the layer depth assigned to each temperature sensor according to its vertical position in the lagoon. As mentioned earlier the temperature probes were deployed every 30 cm from the lagoon surface and therefore in this case Δz_i=30 cm.

RESULTS AND DISCUSSION

SYNOPTIC CONDITIONS

The North American Regional Reanalysis (NARR) (Mesinger et al., 2006) data were used to characterize the meteorological synoptic conditions from 25 to 28 June. During this period, surface winds were weak (less than 5 m s^{-1}) over South Central Kentucky. Accumulated precipitation was 14 mm from 25 to 26 June and it was dry on 27 and 28 June. Figure 2 shows the wind rose extracted from the weather station data for the study period. The wind rose diagram show that about 40% of the time wind had speed less than 4 m s^{-1} and were of southeasterly direction. It is in agreement with the synoptic weather data presented earlier.

BOWEN RATIO ESTIMATES

Bowen ratio was calculated by using a set of observed data from the lagoon. Temperature and relative humidity were measured at the center of the lagoon and vapor pressure and mixing ratios were estimated from these data. Figure 3 shows the vertical temperature differences and the vapor pressure differences. There were differences in temperature between the 0.5 m above the lagoon surface (SFC) and the lagoon surface (0.5 m minus SFC) and between 0.5 and 1.5 m above the lagoon surface (1.5 m minus 0.5 m) for 25 to 28 June. The temperature differences near the surface (0.5 m minus SFC) were in the order of -6°C around midnight while at midday the sign of the temperature differences was reversed to +2°C. The temperature differences of the air at the upper levels (1.5 m minus 0.5 m) were very low by comparison.

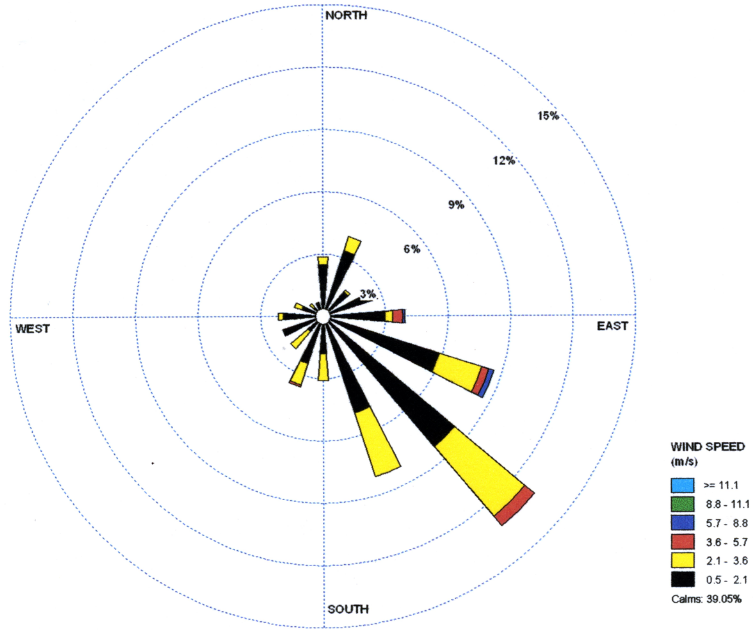

Figure 2. Wind rose diagram for 25 June 12 h to 28 June 10 h.

The largest differences in vapor pressure were, as in temperatures, found from the levels between the 0.5 m and SFC. Differences in vapor pressure between 0.5 m and SFC (0. 5 m minus SFC) were not as pronounced as temperature differences and remained negative for the entire study period. On average these differences in vapor pressure were -10 mb (fig. 3). The sign of vapor pressure differences at these levels was as expected since it was assumed, in the computation of vapor pressure, that air above the water surface was saturated. Thus, the air at 0.5 m is drier than the air at the lagoon surface. On the other hand, at upper levels vapor pressure differences were very small at night and showed two distinct maxima of about 5 mb around midday for 26 and 27 June (fig. 3). The time series for vapor pressure differences at this level indicated that the air at 1.5 m was actually more moist than at 0.5 m. We suggest that this difference is due to the fetch effect. Further explanation is provided in the next section.

In summary, between the 0.5 m and SFC, the air was drier aloft at all times. Moreover, the SFC was warmer at night and cooler during the day compared to the overlying air. The air temperature was slightly higher at 0.5 m compared to 1.5 m and the air was always drier at 0.5 m compared to the 1.5-m

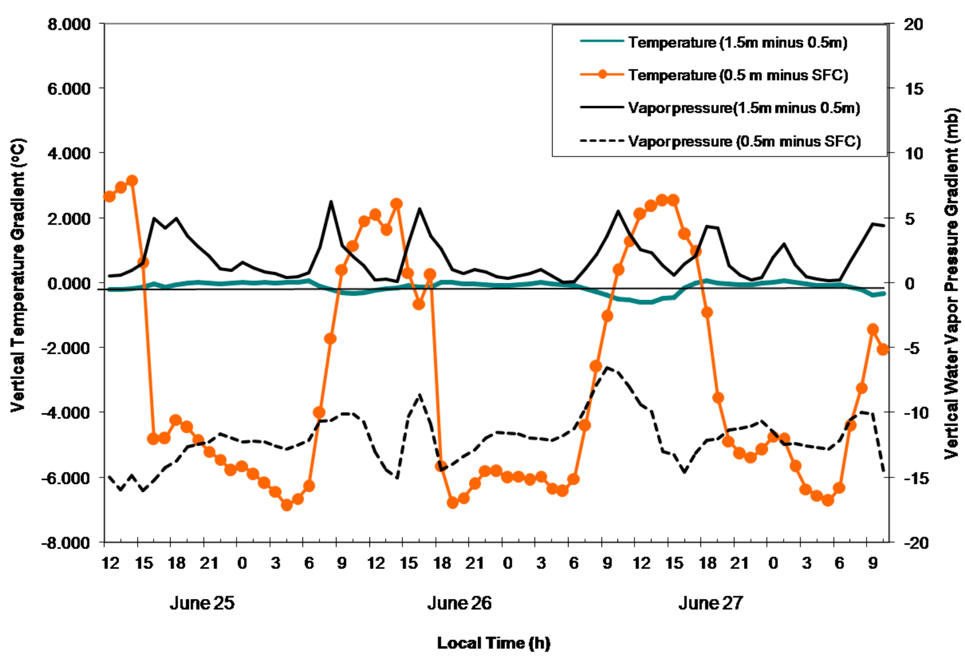

Figure 3. Time series of temperature (°C) (green and orange lines) and vapor pressure (black and dashed lines) (mb) vertical gradients for 25 June 12 h to 28 June 10 h. Differences are taken from levels 1.5, 0.5, and 0.0 m (SFC) above the lagoon surface.

level. Due to the lagoon's large thermal inertia, the SFC remained substantially warmer than the air near the surface at night and cooler at midday due to evaporative cooling.

Figure 4 shows the time series for the two Bowen ratio computations for BR1 and BR2 using the vertical differences of potential temperature and mixing ratios. As expected, during the day, the signs were negative for both BR1 and BR2. At night, however, BR2 was positive while BR1 was near zero or slightly negative. Figure 4 also shows the rapid decrease of Bowen ratio estimated by BR1 at several occasions. These changes occurred after midday and early in the morning. This type of quick changes in Bowen ratio has been the focus of several studies in the past (Ohmura, 1982; Andreas and Cash, 1996; Perez et al., 1999). Here, our purpose is to highlight the differences and or similarities in BR1 and BR2 estimates and how these impacted the estimates of energy fluxes and evaporation. Further discussion is provided in the following two sections.

Energy Fluxes

In the BREB method, energy fluxes are estimated from the energy constraint $R_n - G = LH + SH$ and the definition of Bowen Ratio ($B=SH/LH$) as:

$$LH = \frac{R_n - G}{1+B} \tag{6}$$

$$SH = \frac{B(R_n - G)}{1+B} \tag{7}$$

where LH and SH are the latent heat flux and sensible heat fluxes, respectively. We adhere here to the convention that R_n $-G$, LH, and SH are positive when fluxes are towards the SFC.

Figure 6 shows R_n, LH, and SH for BR1 and BR2 as computed from equations 6 and 7. There is a clear diurnal cycle for all energy fluxes with maximum values of R_n ranging from 500 to 797 W m^{-2}. The maximum fluxes occurred around midday. The time series of LH from BR1 and BR2 displayed very similar tendencies with values ranging from near zero between 21 and 3 h to above 700 W m^{-2} between 7 and 19 h. SH were close to zero in the evening hours to about -50 to -70 Wm^{-2} from 7 to 17 h. In other words, diurnal cycle for SH was significantly muted compared to LH. We also found that fluxes estimated by BR1 and BR2 were comparable. For example, average estimated LH by BR1 and BR2 were about 130 and 146 W m^{-2} and average estimated SH were 16 and 0 W m^{-2} (positive and negative values canceled each other in the latter case), respectively. It was also found that diurnal variations of LH, as estimated by BR1 and BR2, were in phase with each other. This observation also applied to SH.

In summary, SH and LH were in opposite signs during the day. At night, both latent and sensible heat fluxes were very small (consistent with small available energy) and mostly of the same sign. This condition was similar to an oasis effect in which sensible heat fluxes were negative (into the lagoon surface) and latent heat fluxes were positive (away from the lagoon surface) when warm dry air was exposed to an isolated cool source of moisture.

Evaporation Estimates

On 26 June, E reached a maximum value of 0.86 mm h^{-1} as computed from BR1 and BR2 (fig. 6). The corresponding maximum values of E as estimated from the Penman method (Penman, 1948) at 0.5 and 1.5 m were 0.66 and 0.6 mm h^{-1}, respectively. After 12 h, a series of decreasing maxima appeared until 21 h and subsequently E has ceased. On 27 June the maximum values of E were 1.11 and 0.97 mm h^{-1} as estimated from BR1 and BR2, respectively. Based on the Penman method (Penman, 1948), the values were 0.7 and 0.76 mm h^{-1} at 0.5 and 1.5 m, respectively. Therefore, the BREB method estimates were slightly higher than those obtained from Penman's method. It was also found that, like fluxes, Penman-based (Penman, 1948) values of E for two

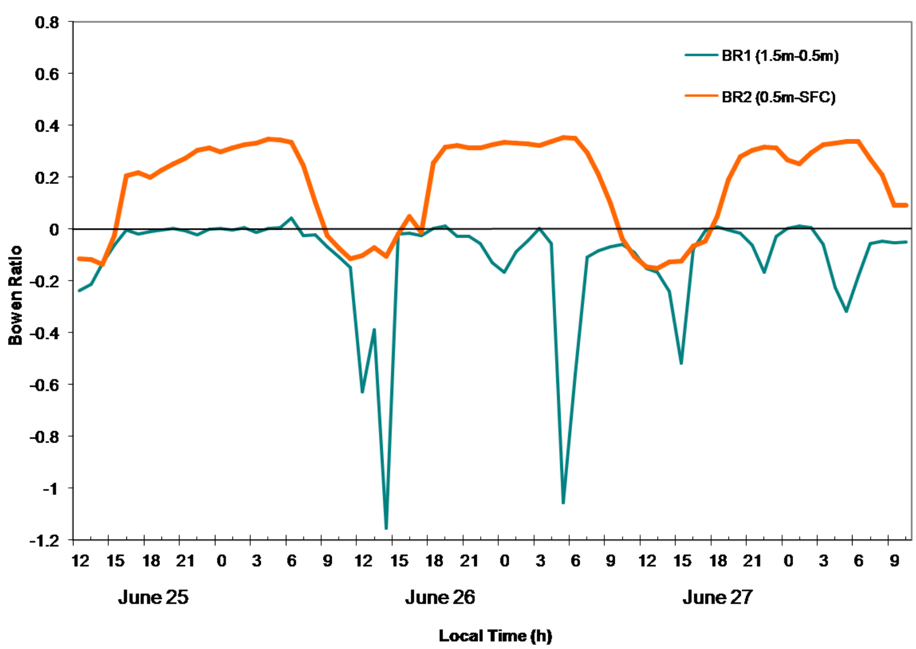

Figure 4. Time series of Bowen ratio for 25 June 12 h to 28 June 10 h, computed from the height differences at 1.5 and 0.5 m (BR1) and from 0.5 m and SFC (BR2).

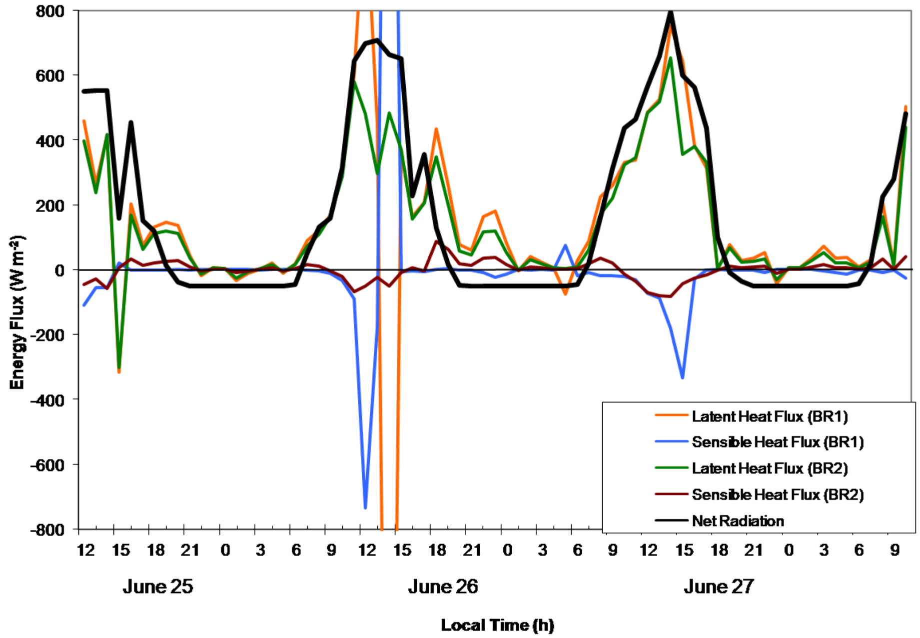

Figure 5. Time series of latent (LH) and sensible fluxes (SH) and net radiation (Rn) (W m-2) for 25 June 12 h to 28 June 10 h computed using BR1 and BR2.

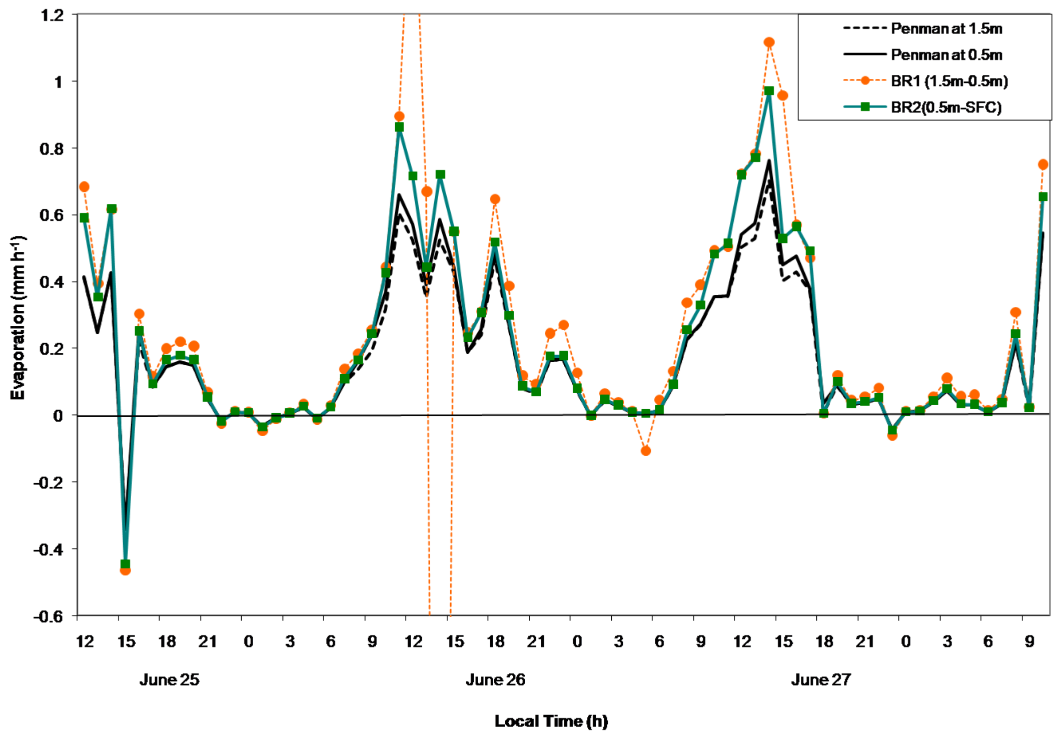

Figure 6. Time series for lagoon evaporation (E) (mm h-1) for 25 June 12 h to 28 June 10 h evaluated with the Penman (Penman, 1948) method at 1.5 and 0.5 m above the lagoon surface and from BR1 and BR2.

heights were also in phase with BR1 and BR2. As expected, comparison of figures 5 and 6 shows in-phase *E* and *LH*.

Table 1 shows 24-h accumulated evaporation for 26 and 27 June. The BREB method has a 1-mm day^{-1} larger estimate of *E* than the Penman method (Penman, 1948). The values obtained for *E* in this study fall within the values reported for swine lagoons in Kansas and Oklahoma for this time of the year (Ham, 1999). Additionally, observed pan evaporation data from a nearby site (Nolin River Lake; NCDC, 2007) in Kentucky were compared to estimated *E* (table 1). The estimated *E* is comparable to observed data for 26 June while it was higher compared to 27 June. The radar data indicated that locations near the Nolin River Lake experienced precipitation on 27 June. We suspect that higher cloud cover in the Nolin River Lake area had suppressed *E*.

Table 1. Daily observed and estimated evaporation from Bowen ratio energy balance and Penman method (Penman, 1948) for 26 and 27 June 2007 at two heights.

Date	Height above Lagoon (m)	BREB Method (mm d^{-1})	Penman Method (mm d^{-1})	Obs. *E* at Nolin River Lake, KY (mm d^{-1}) (NCDC, 2007)
26 June	0.5 m	6.09	5.2	6.6
	1.5 m	2.98	4.81	
27 June	0.5 m	6.07	4.84	1.52[a]
	1.5 m	6.89	4.55	

[a] Precipitation was reported for locations around the Nolin River Lake on 27 June (NCDC, 2008). Low observed *E* from this location is suspected to be linked with enhanced local cloud cover in the vicinity.

Air and Lagoon Temperatures

Figure 7 shows time series for air temperature at 0.5 and 1.5 m above the lagoon surface, temperature at the lagoon surface, and in the lagoon at 0.3-, 0.6-, and 0.9-m depths (below the lagoon's surface). The time evolution of all of these temperatures show a well-defined diurnal cycle with atmospheric temperatures peaking about an hour earlier than their lagoon counterparts. In the lagoon, temperatures show a time lag of about an hour for peak temperatures as well. Physically, this indicates that the lagoon water column was being heated primarily by conduction. The observed diurnal atmospheric temperature variation for this period was between 20°C and 32°C (about 12°C difference). For temperatures in the water, the variation was between 27.5°C and 29.5°C (2°C difference). Additionally, atmospheric temperatures had much larger increasing and decreasing rates than their lagoon counterparts for all days. The lagoon temperature at the 0.9-m depth did not show the well-defined diurnal variation observed at the surface, 0.3- and 0.6-m depths. The vertical temperature stratification of the lagoon became visible between 9 and 18 h for all days. The stratification took place when large atmospheric temperature variations were also observed. On average, air temperatures remained about 2°C higher than lagoon temperatures as radiation increased between 9 and 19 h. In the early morning they remain lower than the lagoon temperatures by about 4°C to 6°C.

Atmospheric Wind Profiles and the Lagoon Thermal Response

Figure 8 shows the time series of wind speed at 0.5 and 1.5 m above the lagoon surface and at the weather station. The wind speeds at the weather station demonstrated diurnal variation and average winds of about 1 to 4 m s^{-1} with intermittent gusts of about 6 m s^{-1}. In addition, wind speeds from the Kentucky Mesonet (http://www.kymesonet.org/) station at Russellville 2 in Logan County (36° 51' N, 86° 54' W) was consulted. It recorded an average wind speed of 2 m s^{-1} with gusts of about 10 m s^{-1} for the period 25 to 28 June. Wind speeds at 0.5- and 1.5-m heights were under 5 and 4 m s^{-1}, respectively. Hence, wind speeds measured over the lagoon at 1.5 m were systematically smaller than those at 0.5 m. With minor variations, figure 8 shows very clearly that the time evolution of the wind at the lagoon at 0.5 and 1.5 m was well correlated with the time evolution of the wind measured at the weather station.

The observed vertical wind profile was probably due to an adjustment of the air near the lagoon surface as it crossed the leading edge of the roughness discontinuity between the ground surface and the lagoon. The lagoon geometry was another factor to be considered since the elevation of the surface of the lagoon did not coincide with the elevation of the ground. Therefore, there was a fetch advection effect below 1.5 m for the wind speed observations. This was consistent with drier and warmer (particularly during day-time) air observed at 0.5 m over the lagoon surface.

To highlight the time correlation between wind activity and the thermal response of the lagoon, figure 8 also included the time series of three vertical temperature differences in

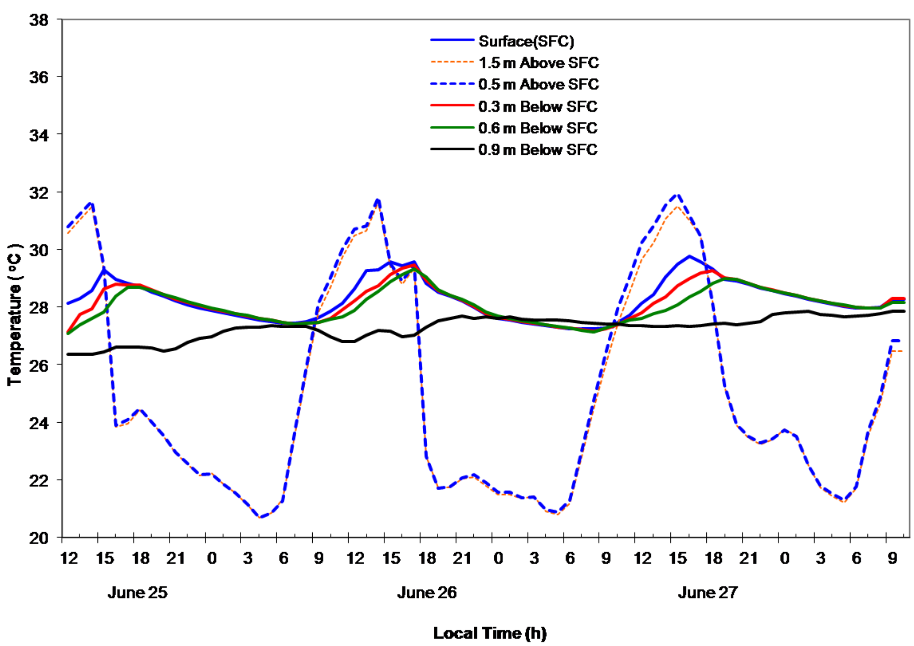

Figure 7. Time series for temperatures (°C) for air at 1.5- and 0.5-m lagoon surface (SFC) and at 0.3-, 0.6-, and 0.9-m depths in the lagoon for 25 June 12 h to 28 June 10 h, 2007.

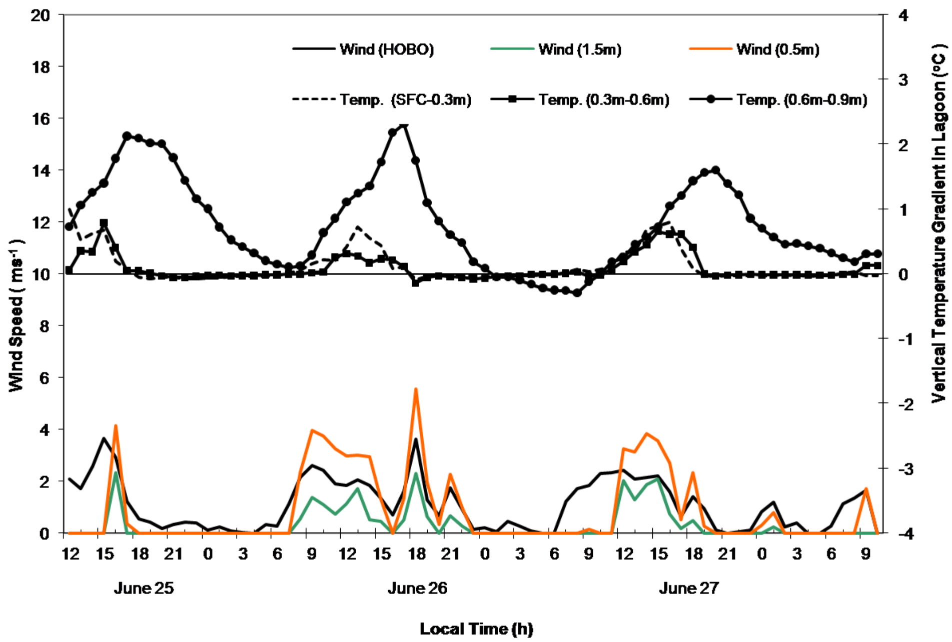

Figure 8. Time series for 25 June 12 h to 28 June 10 h for wind speed (m s^{-1}) at the HOBO weather station and at the center of the lagoon at 1.5- and 0.5-m heights above the lagoon surface. Additionally, vertical temperature differences in lagoon are shown (SFC-0.3 m; 0.3 m-0.6 m and 0.6 m-0.9 m).

the lagoon water column. These differences corresponded to the differences in levels: SFC minus 0.3 m, 0.3 m minus 0.6 m, and 0.6 m minus 0.9 m. It was noted earlier in section 3.5 that the first two vertical temperature differences between the SFC and 0.3 m and the SFC and 0.6 m depths responded relatively faster to heating while the SFC and 0.9 m the lagoon temperature took longer to respond. For this reason the temperature differences between 0.6 m minus 0.9 m reached its peak later than the differences closer to the surface of the lagoon. This condition kept a thermocline of about 2°C between 0.6 and 0.9 m for more than 15 h, starting from hour 9. At upper depth, between SFC and 0.6 m, the vertical temperature differences were of smaller amplitude (less than 1°C) and of shorter duration.

Inspection of both wind and the lagoon thermal stratification revealed that the mixing of lagoon temperatures by the wind stress over the lagoon was not sufficient to overcome the stratification brought about by solar radiation and turbidity of the water column. A criteria for the onset of stratification has been given by Holloway (1980) and it states that stratification will ensue if $u^3 \leq 51h - 89/c$, where h is the depth of the water column and c the extinction coefficient which measures the e-fold depth of shortwave radiation penetration of the water column. Holloway (1980; fig. 8) constructed a family of curves for the above criterion. He found that for a water column of 2 to 3 m with an extinction coefficient equal or larger than 2.0 m^{-1} along with wind speeds between 4 and 5 m s^{-1} would guarantee thermal stratification. In the present study, wind speeds over the lagoon did not surpass 5 m s^{-1} during midday. It is concluded that in order to break the thermal stratification, wind speeds greater than 5 m s^{-1} are required. The observed time evolution of vertical stratification resembled modeling results applied to shallow and fetch-limited water bodies (e. g., Condie and Webster, 2002).

Lagoon Heating, Bowen Ratio, and Evaporation

In this section, the relationships between the lagoon and the atmosphere are further investigated. The energy term in regards to the lagoon heating is shown as a scatter plot between the net radiation, R_n , and the lagoon heating, G (fig. 9). These two variables showed a significant correlation for the study period with R^2 = 0.664. This correlation revealed that as R_n surpassed 200 W m^{-2}, heating of the lagoon became positive. As previously defined, R_n, is a linear combination of solar radiation and a correction term (see section 2.3) that took the albedo and the outgoing infrared

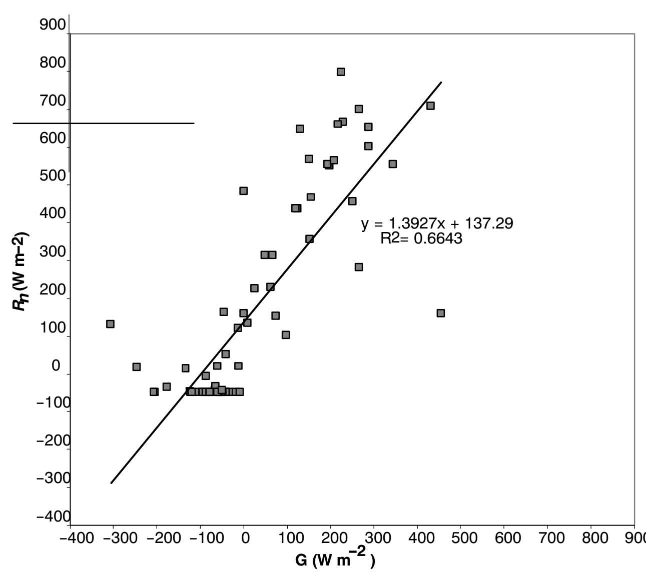

Figure 9. Scatter plot between net radiation (R_n) and lagoon heating (G) (W m^{-2}) for 25 June 12 h – 28 June 10 h.

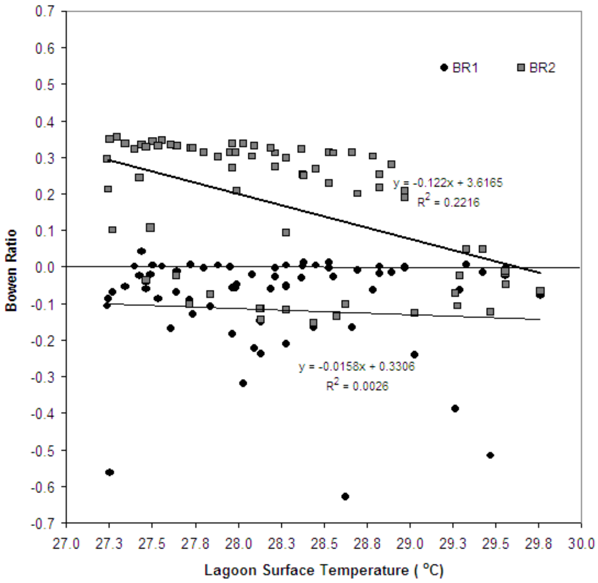

Figure 10. Lagoon surface temperature vs. Bowen ratio at 0.5 m (BR1) and 1.5 m (BR2) above the lagoon surface.

radiation from the lagoon surface into account (Ham, 1999). Therefore, the results reflected an approximation to the true relationship between G and R_n.

Figure 10 shows an inverse relationship between Bowen ratio as computed for the BR1, the BR2, and the temperature of the lagoon surface. Small R^2 and the inverse relationship imply that the increase was not sufficient to establish a clear dependence of *LH* and *SH* on lagoon temperature. However, a relatively stronger inverse relationship between BR1, BR2 and G was found (fig. 11). A larger R^2 was found for BR2 (0.658) and G than BR1 and G (0.08). As G increased, sensible heat flux from the lagoon decreased faster than latent heat flux making Bowen ratio values smaller. This also suggested that E has increased as G increased with the progression of the day. Separate analysis of data also verified this assertion (not shown).

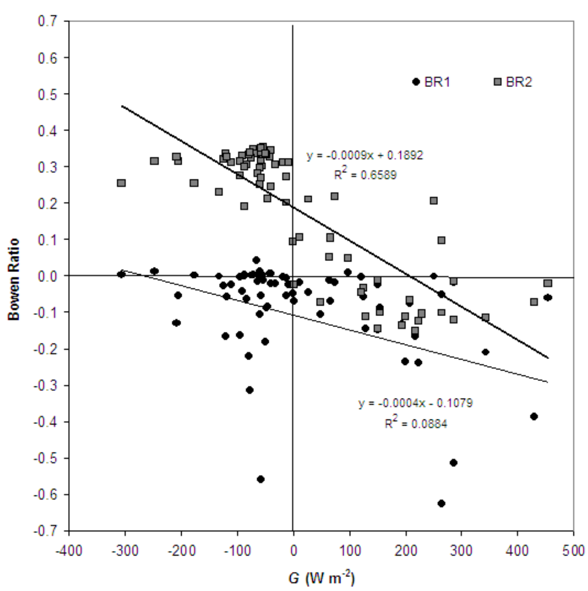

Figure 11. Lagoon surface heating, G, vs. Bowen ratio at 0.5 m (BR1) and 1.5 m (BR2) above the lagoon surface.

Figures 12 and 13 show the same type of relationships as figure 11 except that the G is replaced by vertical temperature differences at two depths. Again BR2 in both cases (figs. 12 and 13) had larger R^2 values (0.65 and 0.50) compared to BR1 (0.13 and 0.07). Again, an inverse relationship was evident between Bowen ratio and the vertical temperature differences. These results indicated that the atmosphere respond to G rather than to the lagoon surface temperature. During the daylight hours, as lagoon heating increases, Bowen ratio (BR2) decreases which means more energy was used in evaporation that may cool the lagoon surface and destroy the stratification. This phenomenon was observed at about 18 h for all days. At night, Bowen ratio remained small with both sensible and latent heat fluxes towards the atmosphere.

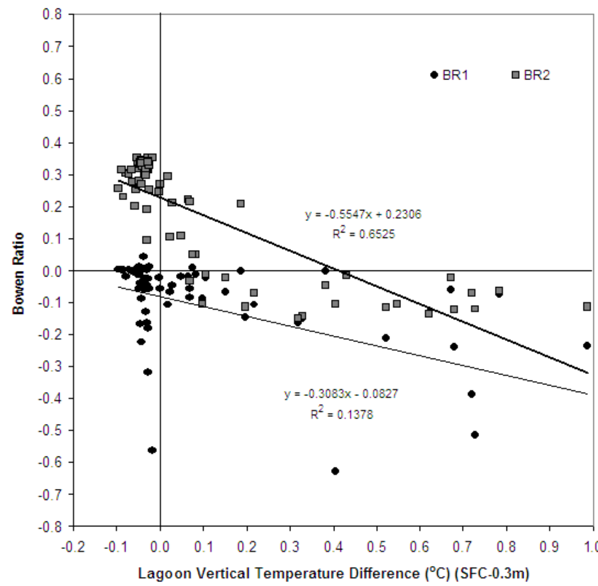

Figure 12. Temperature at 0.3-m deep in the lagoon subtracted from lagoon surface temperature vs. Bowen ratio at 0.5 m (BR1) and 1.5 m (BR2) above the lagoon surface.

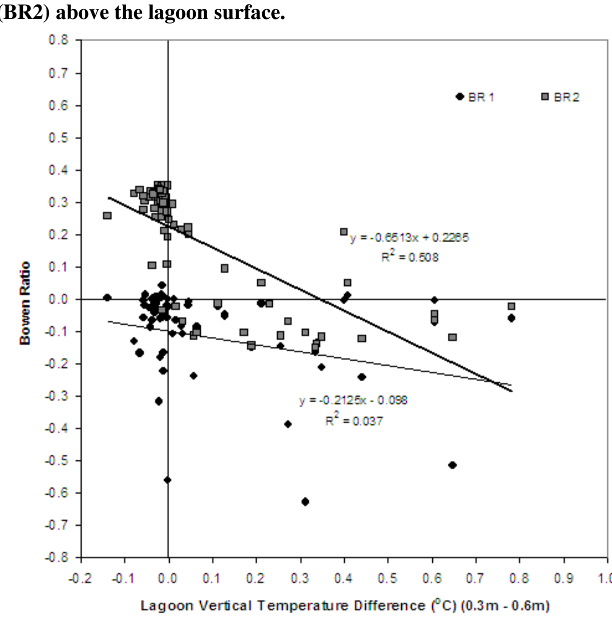

Figure 13. Temperature at 0.6-m depth in the lagoon subtracted from temperature at 0.3-m depth vs. Bowen ratio at 0.5 m (BR1) and 1.5 m (BR2) above the lagoon surface.

Conclusion

Measurements of water vapor fluxes can be used as proxies for studying the emissions of VOC emissions (Wilson et al., 2001; Griffith et al., 2002; DeSutter and Ham, 2005). Using relatively simple equipment, we estimated Bowen ratio and evaporation from a swine waste lagoon for 25 through 28 June 2007. In addition, the influence of thermal stratification within the lagoon on Bowen ratio and evaporation was investigated.

The results for this study were useful because it established, at least conditions prevailing during the data collection period, that the Bowen ratio is part of an indirect atmospheric control on evaporation rates. Evaporative cooling of the upper water layers could produce an imbalance of existing thermal stratification. We suggest that this could also potentially lead to the breaking down of the stratification and may influence the emission rates of dissolved gases. Therefore, we can expect to find some link between the evolution of Bowen ratio and the emissions from the lagoon. The results reported in this study form the basis of a broader research project aimed at establishing a useful relationship between the emissions of pollutants and the atmospheric and solar radiation controls.

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